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RESEARCH MEMORANDUM

A FLIGHT STUDY OF REQUIREMENTS FOR SATISFACTORY LATERAL OSCILLATORY CHARACTERISTICS OF FIGHTER AIRCRAFT

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SUMMARY

A conventional fighter airplane, fitted with special servo devices for varying in flight the dihedral effect, the static directional stability, and the directional damping was used in a pilot-opinion survey involving 12 pilots. Results of the investigation, showing boundaries which define satisfactory and tolerable lateral oscillatory characteristics, are presented. The boundaries are in the form of relations between the cycles to damp to half amplitude and the ratio of the amplitude of the bank angle to that of the side velocity in the oscillatory mode. In addition, the lateral aperiodic motions encountered during the investigation and their relations to the pilot opinions are discussed.

INTRODUCTION

The problem of providing suitable numerical criteria against which the measured or predicted stability and control characteristics of piloted airplanes can be graded has been the subject of many investigations in the past. This work led to the formulation of formal flying-qualities specifications by the Armed Services (references 1 and 2). The experience upon which these requirements are based, however, was gained with airplanes of conventional configuration (propeller-driven, straight-wing aircraft) that operated mainly below 30,000 feet. The introduction of the jet propulsion engine lifted both the operating speeds and altitudes to a point where radical plan-form changes were required to realize the potentialities of the engine. The higher operating altitudes (40,000 feet) and the absence of a propeller are factors tending to reduce the damping of both the longitudinal and lateral oscillations. At present, the damping of the longitudinal motions of operational aircraft has not generally been reduced to the point where the pilots have found the attendant overshoot objectionable. This is not the case with the lateral-directional oscillations, however, since there have been a number of cases of pilot objection to the lateral oscillatory characteristics of aircraft in which not only low damping but excessive rolling was noted.

Previous work, reported in reference 3, described a variable stability test vehicle used to evaluate the maximum and minimum values of effective dihedral that could be tolerated. In addition, it was noted that some conditions considered good by the pilots fell within the unsatisfactory region of the period-damping criteria of references 1 and 2, while other conditions considered unsatisfactory by the pilots fell within the satisfactory region. There were indications that, in addition to damping, the roll-to-sideslip ratio had a strong influence on the pilots' opinions. Therefore, this test vehicle was revised to provide control of both the directional damping parameter (C_{n_r}) and the weathercock stability parameter (C_{n_β}) as well as the effective dihedral, so that large changes in the damping and amplitude of the lateral oscillations could be provided. Correlation of these large changes in the damping and amplitude of the lateral oscillation could then be made with the opinions of several pilots with regard to the lateral handling characteristics, thereby affording a measure of the satisfactory and tolerable lateral dynamic stability characteristics.

It is the purpose of the present report to present the results of this investigation to determine limiting lateral dynamic stability characteristics for aircraft which, in the opinion of pilots, have satisfactory flying qualities.

NOTATION

Γ_e	effective dihedral angle, degrees
C_{l_β}	rate of change of rolling-moment coefficient with sideslip angle, per degree
C_{n_β}	rate of change of yawing-moment coefficient with sideslip angle, per degree
C_{n_r}	rate of change of yawing-moment coefficient with $\frac{rb}{2V}$
r	yawing velocity, radians per second
p	rolling velocity, radians per second

β	sideslip angle, degrees
φ	angle of bank degrees
A_y	lateral acceleration of pilot's seat, g units
v	side velocity $\left(\frac{\beta V}{57.3}\right)$, feet per second
v_e	equivalent side velocity $(v\sqrt{\sigma})$, feet per second
V	true airspeed, feet per second
V_i	indicated airspeed, knots
$T_{\frac{1}{2}}$	time for the lateral oscillations to damp to half amplitude, seconds
T_2	time for the lateral oscillations to double amplitude, seconds
T_{2a}	time for the unstable aperiodic mode to double amplitude, seconds
$C_{\frac{1}{2}}$	number of cycles for the lateral oscillations to damp to half amplitude
C_2	number of cycles for the lateral oscillations to double amplitude
$\lvert\varphi\rvert$, $\lvert\beta\rvert$, $\lvert v\rvert$, etc.	amplitude of the indicated quantities in the oscillatory mode
σ	air-density ratio
b	span, feet
δ_a	pilot-applied total aileron angle (sum of up- and down-aileron angles), right when right-hand aileron is up, degrees
δ_r	pilot-applied rudder angle, right when trailing edge is to right, degrees
F_a	aileron stick force, pounds
F_r	rudder-pedal force, pounds

Flight Conditions

Landing approach — V_i = 120 knots; flaps and landing gear retracted; pressure altitude = 7000 feet; power for level flight

Cruising — V_i = 200 knots; flaps and landing gear retracted; pressure altitude = 7000 feet; power for level flight

EQUIPMENT AND INSTRUMENTATION

A photograph of the test airplane is shown in figure 1. Flight measurements of the quantities presented herein were made with standard NACA photographically recording instruments.

The apparatus for varying the dihedral effect is described in detail in reference 3. The device for varying the static directional stability and the damping in yaw operated essentially in the same manner as did the dihedral apparatus, except that the rudder was deflected instead of the ailerons. The devices caused rolling and yawing moments to be exerted on the airplane (by deflecting the ailerons and rudder) which were proportional to pertinent quantities of motion. Thus, in order to change the dihedral effect, the equipment deflected the ailerons in proportion to the sideslip angle, and to change the static directional stability the rudder was deflected in proportion to the sideslip angle. The rudder was deflected in proportion to the yawing velocity in order to cause a change in the damping in yaw. The control surfaces were deflected by electrical servo equipment through mechanical differentials; thus, the servo deflected the surfaces without moving the pilot's controls, and the net rudder or aileron deflection was the algebraic sum of that due to the pilot and that due to the servo. Rudder and aileron tabs were deflected in proportion to that part of the control deflection due to the respective servo, so that the hinge moments (and therefore the control forces) due to the servos were minimized.

During the investigation five settings of dihedral effect were used which varied Γ_e, the stick-fixed effective dihedral angle, from about 17.8° to -6.2°. Three static directional stability settings were investigated, which provided a range of C_{n_β} with pedals fixed from about 0 to +0.0014 per degree. Four settings of the directional damping were used, varying C_{n_r} with the controls fixed from about −0.19 to +0.06.

The aileron control characteristics in steady, straight sideslips for the minimum, the normal, and the maximum effective dihedral settings are shown in figures 2 and 3. The rudder control characteristics in sideslips for the minimum, the normal, and the maximum static directional stability settings are shown in figures 4 and 5. It is seen that the control positions and forces varied smoothly with sideslip angle and that the dihedral effect and static directional stability, as evidenced by the slopes of the aileron and rudder position curves, respectively, were varied over a wide range. The effect of changing the directional damping setting is demonstrated in figure 6, which shows typical time histories of lateral oscillations with normal dihedral effect and directional stability. All lateral-oscillation data presented herein were obtained with the pilot's controls fixed.

To demonstrate the effectiveness of the servo systems in changing the dynamic flight characteristics of the test aircraft, sample time histories of various maneuvers are shown in figures 7 through 10. Time histories of pedals-fixed aileron rolls are shown in figures 7 and 8. It is seen that the characteristics were varied from those of a nearly two-control configuration with very little adverse sideslip to those of a configuration which exhibited rolling-velocity reversals.

Figures 9 and 10 show sample time histories of lateral oscillations which were excited by returning the controls to the wings-level trim position from a steady sideslip. The natural period was varied from a minimum of about 2 seconds to a maximum measurable value of 11.4 seconds, and the damping was varied so that the motions varied from nearly "dead beat" to the unstable condition in which the amplitude of the oscillations doubled in 5.4 seconds.

In tests of the equipment it was found that as the static directional stability was increased, the damping in yaw apparent during oscillations was reduced somewhat. This was due to a small amount of phase lag between the sideslip sensing vane and the rudder servo. This phenomenon is not believed to detract from the usefulness of the equipment for the purposes of this investigation.

PROCEDURE FOR OBTAINING PILOTS' OPINIONS

Opinions of the lateral handling qualities were obtained from 12 pilots, 2 from the Air Force, 4 from the Navy, 1 from the Cornell Aeronautical Laboratory, and 5 from the NACA. All were highly experienced with fighter-type aircraft.

The pilots were asked to assign a numerical rating to each of the configurations investigated (i.e., each combination of C_{l_β}, C_{n_β}, C_{n_r} and flight condition), and they were given a set of specific questions to answer with the aim of obtaining the reasons for their ratings. These questions were answered while flying in the cruising condition. The list of questions is presented in the appendix. The rating system was as follows:

Numerical rating	Adjectival rating
1 2 3	Good
4 5 6	Tolerable
7 8 9	Intolerable

The adjectival ratings were provided as guides in choosing the numerical ratings.

A "good" configuration was one which was pleasant to fly, completely satisfactory.

"Tolerable" described a configuration usable in normal fighter operation but not necessarily pleasant to fly.

"Intolerable" meant that the configuration was not usable in normal fighter operation.

So that the pilots, in forming their ratings, would consider the airplane for the same operational uses, separate ratings were made considering the airplane for each of the following specific uses:

(a) Cross-country contact flying
(b) Cross-country instrument flying
(c) Gunnery
(d) Landing-approach contact
(e) Landing-approach on instruments

Ratings for uses (a) and (b) were made while flying in the cruising flight condition. In order to form their opinions, the pilots were asked to fly straight and level and to make typical mild maneuvers.

Ratings for use (c) were also made while flying in the cruising flight condition. The pilots were asked to form their opinions on the basis of the following maneuver. An abrupt change of course was made to a chosen target (a point on the horizon such as a mountain top), and the gunsight reticle was held on target for an appropriate length of time.

Ratings for uses (d) and (e) were made while flying in the landing-approach flight condition. No actual landings were made, however.

The final cruising-condition ratings used in the following discussion were obtained by numerically averaging the ratings for uses (a), (b), and (c) above for all the pilots. The final landing-approach ratings were similarly obtained with the ratings for uses (d) and (e).

Because the aileron-control forces required in aileron rolls with the test airplane were high in comparison with more modern fighters, the pilots were requested to try not to penalize any particular configuration on account of high aileron forces.

RESULTS AND DISCUSSION

Comparison of Oscillatory Characteristics With the Pilots' Opinions

The average pilot ratings, together with the measured oscillatory characteristics of those configurations which exhibited well enough defined oscillations to be amenable to measurement are shown in table I. The standard deviation of the pilot rating is also included to indicate the scatter in opinions among the pilots.

The lateral-directional requirements of references 1 and 2 which are pertinent to the configurations of table I are:

1. The oscillatory requirement, which is in the form of a boundary between satisfactory and unsatisfactory combinations of the time to damp to half amplitude, $T_{1/2}$, and the period of the oscillations

2. The requirement which prohibits rolling-velocity reversals in pedals-fixed aileron rolls

3. The requirement which limits the adverse yaw during pedals-fixed aileron rolls

Figure 11 shows how the configurations of table I compare with these three requirements. The oscillatory boundary is shown as a relation between the period of the oscillations and the damping expressed as $\frac{1}{T_{1/2}}$ or $\frac{1}{T_2}$ (so that unstable points can be shown on a continuous scale). The period and $\frac{1}{T_{1/2}}$ of those configurations given in table I are plotted in this figure. Points for both the landing approach and the cruising conditions are included. The nature of the points (solid or open) shows the pilots' opinions of the configurations. If the average rating for a particular configuration and condition was equal to or less than 5.0 (midway between good and intolerable on the rating scale), it was called satisfactory and was plotted in figure 11 as an open point. If it was greater than 5.0, it was called unsatisfactory and was plotted as a solid point. If the configuration exhibited rolling-velocity reversals, a horizontal bar is shown through the point. If data from pedals-fixed aileron rolls from level, unaccelerated flight indicated that the adverse yaw requirement would be violated, a vertical bar is shown through the point. It is seen that the three pertinent requirements are not entirely consistent with the pilots' opinions. A few of the configurations which were unsatisfactory in the opinion of the pilots were satisfactory by the three requirements, and more than half of the configurations which were satisfactory in the opinion of the pilots were unsatisfactory by the requirements. It is necessary to recognize, however, that the division of pilot opinion into satisfactory and unsatisfactory categories is an oversimplification in view of the spread of pilot opinion, as shown by the standard deviations of table I, which is large for some configurations.

It is seen from figure 11 that the adverse yaw requirement is the cause of the inconsistency insofar as the points rated satisfactory by the pilots are concerned. A study of the data indicated that simply increasing the allowable adverse yaw, however, would not remedy the situation — more unsatisfactory points would be admitted than satisfactory ones. Thus, it would appear that the adverse-yaw requirement should not be a consideration for this particular set of data, and that some method of separating the configurations, other than by the three afore-mentioned requirements should be sought.

Figure 12 is a plot of the damping parameter, $\frac{1}{C_{1/2}}$, against the rolling parameter, $\frac{|\varphi|}{|v_e|}$, for the same data. This method of plotting was found to be the most efficient of several methods tried in separating the points according to pilot rating. It is seen that the line of demarkation between satisfactory and unsatisfactory configurations, which has been faired by eye, is reasonably well defined and is not affected by the rolling-velocity-reversal requirement.

Figure 13 is a similar plot which separates tolerable configurations from intolerable ones. If the average pilot rating was 6.5 or greater, the point was made solid; if it was less than 6.5, the point was made open. Here again the line of demarkation is well defined.

Unfortunately, there were no average ratings of good (1, 2, or 3 on the rating scale), so a similar boundary between good and tolerable configurations could not be formed.

A plot of $\frac{1}{C_{1/2}}$ against $\frac{|\varphi|}{|\beta|}$ (one of the possible criteria suggested in reference 3) was found to give good results for a given flight condition (landing approach or cruising), but the results for the two flight conditions were not in agreement. When $\frac{|\varphi|}{|\beta|}$ was converted to $\frac{|\varphi|}{|v|}$ $\left(v = \frac{\beta V}{57.3}\right)$ and plotted against $\frac{1}{C_{1/2}}$, the results of separating tolerable configurations from intolerable ones agreed very well for the two flight conditions. It is realized, of course, that the airplane was not rated for the same uses in the two flight conditions; however, it seems logical that the oscillatory rolling characteristics would affect the pilots' ratings in the same manner during a landing approach as during cross-country flying or gunnery runs. Also, it seems logical to use $\frac{|\varphi|}{|v|}$ because side-gust disturbances do not occur in the form of changes in β, but rather they occur in the form of changes in v.

One objection to $\frac{|\varphi|}{|v|}$ as a criterion, however, is that the value of $\frac{|\varphi|}{|v|}$ for a specific airplane lacks the feature of growth with altitude for a constant indicated airspeed. The altitude was kept constant during this investigation. However, evidence exists in the literature (see reference 4) that pilots often notice an objectionable increase in the rolling motion in rough air as the altitude is increased. This has been substantiated by unpublished pilots' comments made during flight tests at the Ames Laboratory of a swept-wing operational fighter.

If $\frac{|\varphi|}{|v|}$ is divided by the square root of the density ratio, it becomes $\frac{|\varphi|}{|v_e|}$, where v_e is the equivalent side velocity. In general, $\frac{|\varphi|}{|v_e|}$ does increase with altitude. Such a change in variable seems, on the surface, to be strictly arbitrary, but support for such a change is found in atmospheric gust data. Reference 5 presents statistical information which shows that the effective gust velocity does not vary with altitude in turbulent air conditions, and the effective gust velocity referred to is in the form of an equivalent airspeed.

In order to examine further the plot of $\frac{1}{C_{1/2}}$ against $\frac{|\varphi|}{|v_e|}$, plots were made of $\frac{1}{C_{1/2}}$ against average pilots' rating for various intervals of $\frac{|\varphi|}{|v_e|}$. These plots are presented in figure 14. Both the landing-approach data and the cruising data are shown. It is seen that for each interval of $\frac{|\varphi|}{|v_e|}$ (with one exception) the pilot rating can be taken as a function of $\frac{1}{C_{1/2}}$ alone, and that in all cases the trend is such that an increase in $\frac{1}{C_{1/2}}$ brought about an improvement in the flying qualities in the pilots' opinions. The one exception mentioned is the lowest interval of $\frac{|\varphi|}{|v_e|}$ $\left(0.05<\frac{|\varphi|}{|v_e|}<0.15\right)$, in which distinction is made between two static directional-stability settings. It is obvious that the pilots preferred the higher directional stability at a given value of $\frac{1}{C_{1/2}}$. Examination of the pilots' answers to the questions indicates that the preference is due to the fact that coordination was easier in turn entries with the higher directional stability, which, in turn, was apparently due to lower rudder sensitivity in yaw.

The values of minimum satisfactory or tolerable damping determined in figures 12 and 13, respectively, agree reasonably well with that reported in reference 6 $\left(\frac{1}{C_{1/2}} = 0.735\right)$ over the range of $\frac{|\varphi|}{|v_e|}$ tested during that investigation (about 0.05° to 0.40° per foot per second).

The results presented in figures 12 and 13 indicate the same trends of pilot opinion as pointed out in reference 3. However, quantitative disagreement was apparent when the results of reference 3 were compared with the present results on the basis of $\frac{|\varphi|}{|v_e|}$ and $\frac{1}{C_{1/2}}$. The results of reference 3 showed that the pilots' opinions of a given combination of $\frac{|\varphi|}{|v_e|}$ and $\frac{1}{C_{1/2}}$ were more favorable than those indicated in figures 12 and 13. Pilots who participated in both investigations believe that the reason for the quantitative disagreement is that, during the investigation reported in reference 3, they had a tendency to form their opinions relative to the normal airplane (with apparatus inoperative) in spite of efforts to keep their opinions on a more absolute basis. During the present investigation, due to the much greater number of configurations flown, it was easier to keep their opinions on an absolute basis; the opinions formed on any one configuration did not tend as strongly to affect the opinions of another configuration. For this reason, the results presented in figures 12 and 13 are considered more reliable, quantitatively, than those of reference 3.

In reference 7 it was reported that the lateral linear acceleration was the primary quantity noticeable to the pilot during snaking oscillations when no unusual rolling was present. An attempt was made, with no success, to separate the data presented in this report on the basis of $\frac{|A_y|}{|v_e|}$ and $\frac{|A_y|}{|\beta|}$ plotted against $\frac{1}{C_{1/2}}$. Thus, it is believed that the angle of bank is the primary quantity sensed by the pilots, but that when rolling is slight, or when visual reference is not available, the lateral acceleration becomes important.

In view of the above discussion, the boundaries from figures 12 and 13 are combined in figure 15 and are presented as a proposed tentative criterion for grading the lateral oscillatory characteristics of fighter aircraft.

In figure 16, a comparison is made between the proposed tentative criterion and the lateral-oscillatory characteristics of several present-day military and research airplanes. The quantitative data and pilots' opinions shown in figure 16 were obtained from various Air Force, Navy, industry, and NACA sources. The comparison shows that the criterion is reasonable in principle for grading the characteristics of actual present-day airplanes. The quantitative discrepancy, shown by the large number of satisfactory points which fall in the unsatisfactory but tolerable area is probably caused by differences in definition of terms used in the grading systems.

Figure 17 shows a comparison of the tentatively proposed criterion with other requirements of the past and present (references 1, 2, 4, 8, 9, and 10). The comparison is made on the familiar plot of $T_{1/2}$ against period. It should be recalled, in connection with figure 17, that the present investigation did not cover the period range below about 2 seconds; it is felt, however, that the information can be used down to a 1.0-second period. The general trend, it appears, is toward more and more stringent requirements with regard to damping.

It is believed that future tests should be made with equipment for varying other parameters (such as the damping in roll) which would allow $\frac{|\varphi|}{|v_e|}$ to be varied over a wide range without causing rolling velocity reversals during aileron rolls. It is also believed that a higher performance aircraft than that used for this investigation should be used so that lower values of the oscillation period could be investigated and a better comparison of $\frac{|\varphi|}{|v_e|}$ and $\frac{|\varphi|}{|\beta|}$ as flying-qualities criteria could be made. In future tests the altitude should be varied over a wide range.

Pilots' Opinions – Aperiodic Characteristics

Some of the configurations tested with reduced dihedral effect, particularly those with low directional stability, exhibited unstable aperiodic motion. The pilots' opinions of these configurations were of the nature of objections to spiral divergence. As the directional stability was increased, however, the pilots' rated the flying qualities as remarkably improved. On the surface, this appeared paradoxical because it is usual to expect the spiral instability to increase with increasing directional stability. Brief computational checks indicated that, with the minimum directional stability used and the reduced values of dihedral effect, the oscillatory mode could be expected to be replaced with two aperiodic modes, one of which would be quite unstable. The mode usually associated with the term "spiral" was found from the computations to be stable. Thus, it was undoubtedly the effect of the unstable aperiodic mode which caused the pilots' objections and not the usual spiral mode.

The particular settings of the directional stability, the dihedral effect, and the directional damping chosen for the investigation afforded only six combinations of flight conditions and apparatus settings that exhibited measurable aperiodic divergence. The results of flight measurements of the time required to double the amplitude for these combinations together with the average pilot ratings, the standard deviations of the pilot ratings, and the flight conditions are given in table II. Figure 18 shows the average pilot rating plotted as a function of the time to double amplitude for the landing-approach condition. The data shown in the table for the cruising condition indicate wide disagreement with the landing-approach points. The pilots apparently would tolerate greater rates of aperiodic divergence in the landing-approach condition than in the cruising condition. The reason for the disagreement is not apparent. Figure 18 indicates that the minimum values of the time to double amplitude in the landing-approach condition were about 3.4 and 2.6 seconds for satisfactory characteristics and tolerable characteristics, respectively. A 4.0-second minimum is specified in references 1 and 2. Thus, it appears that the order of magnitude of the present requirement is reasonable.

CONCLUSIONS

From results of a pilot-opinion investigation with a conventional airplane fitted with equipment for varying in flight the dihedral effect, the directional stability, and the directional damping, the following conclusions can be drawn:

1. Other oscillatory characteristics remaining constant, as the damping was increased the pilots rated the airplane characteristics as being more satisfactory.

2. Satisfactory and tolerable lateral-oscillatory characteristics could be separated from unsatisfactory and intolerable characteristics by relations between $\frac{1}{C_{1/2}}$, the reciprocal of the cycles required to damp to half amplitude, and $\frac{|\varphi|}{|v_e|}$, the ratio of the amplitude of the angle of bank in the oscillatory mode to that of the equivalent side velocity. Tentative recommendations for lateral oscillatory requirements are presented in figure 15.

3. When rolling amplitude was low $\left(\frac{|\varphi|}{|v_e|}\right.$ less than about 0.2° per foot per second$\left.\right)$, the minimum tolerable damping and minimum satisfactory damping was described by $\frac{1}{C_{1/2}}$ equal to 0.2 and 1.0, respectively.

4. The maximum tolerable and maximum satisfactory values of $\frac{|\varphi|}{|v_e|}$, regardless of damping, were about 0.75 and 0.55, respectively.

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APPENDIX

QUESTIONS ANSWERED BY PILOTS DURING INVESTIGATION

A. Straight and level flight in smooth air:

1. Does airplane tend to wander off course, keep diverging in one direction or the other; is it hard to trim?

    a. If so, is it seriously objectionable?
    b. Is unusual or excessive use of controls required to keep on course?

B. Straight flight through rough air:

1. Does airplane roll excessively?
2. Yaw excessively?
3. Is ratio of roll to yaw too great?
4. What is best control procedure?

    a. Closely or loosely controlled?
    b. Primarily aileron, primarily rudder, or coordinated rudder and aileron?

C. Abrupt pedals-fixed turn entries:

1. Can pedals-fixed turn entries be made satisfactorily?

    a. If not, why?

        1. Rolling velocity not high enough or reverses?
        2. Adverse yaw too great?
        3. Other reasons?

D. Abrupt coordinated turn entries:

1. Is it difficult to coordinate in turn entries?

    a. If so, why?

        1. Rudder too touchy in producing roll?
        2. Rudder too touchy in producing yaw?
        3. Rudder forces too low as compared to aileron forces?
        4. Rudder forces too high?
        5. Oscillations easily excited?
        6. Other reasons?

E. Steady turns:

1. Are rudder forces too high?

F. Lateral-directional oscillations:

1. Can oscillations be damped without excessive pilot effort?
2. Do you think damping would be easier if period of oscillations were longer?

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TABLE I.– PILOTS' OPINIONS OF THE CONFIGURATIONS EXHIBITING MEASURABLE OSCILLATORY CHARACTERISTICS

(a) Landing-approach condition

P (sec)	$T_{1/2}$ (sec)	$\frac{1}{C_{1/2}}$ (per cycle)	$\frac{\lvert\varphi\rvert}{\lvert\beta\rvert}$	$\frac{\lvert\varphi\rvert}{\lvert v_e\rvert}$ (deg/ft per sec)	Average pilot rating	Standard deviation of pilot rating
3.7	13.35	0.28	0.77	0.21	7.6	1.80
3.7	6.4	.578	.86	.24	6.8	1.63
3.7	3.1	1.19	1.13	.31	5.9	1.72
3.7	1.475	2.51	1.32	.366	4.6	1.54
6.5	3.86	1.68	2.17	.61	5.6	3.67
6.8	2.97	2.29	2.31	.64	7.5	.68
7.4	2.7	2.74	2.46	.68	6.7	1.56
5.5	5.8	.95	1.53	.43	6.8	3.12
5.35	3.78	1.42	1.65	.47	5.7	1.41
5.5	2.77	1.99	1.61	.46	4.5	1.57
5.5	1.82	3.02	1.63	.46	4.5	1.86
3.4	11.35	.30	1.08	.30	6.1	.84
3.3	3.70	.89	1.03	.29	5.6	1.80
3.3	2.31	1.43	1.26	.36	3.6	1.73
5.0	16.45	.30	2.48	.69	9.0	0
5.0	4.75	1.05	3.05	.86	7.5	1.31
5.2	2.85	1.82	3.37	.94	6.5	1.68
4.05	15.95	.25	2.22	.62	9.0	0
4.1	8.20	.50	2.51	.70	6.7	1.44
4.3	4.30	1.00	2.57	.72	6.8	1.48
4.2	2.98	1.41	2.76	.77	5.7	1.60
3.0	27.20	.11	1.43	.40	7.7	1.48
3.0	5.35	.57	1.65	.47	6.4	1.52
3.0	3.10	.97	1.59	.44	4.7	1.52
4.0	7.55	.53	3.63	1.0	8.0	.79
4.0	3.75	1.08	3.44	.97	7.7	.86
3.6	8.20	.44	3.11	.87	8.0	1.00
3.6	2.16	1.66	3.49	.98	6.5	1.26
2.7	28.70	.94	2.32	.64	7.0	1.53
2.7	4.95	.55	2.30	.64	6.5	1.39

TABLE I.- CONCLUDED

(b) Cruising condition

P (sec)	$T_{1/2}$ (sec)	$\frac{1}{C_{1/2}}$ (per cycle)	$\frac{\lvert\varphi\rvert}{\lvert\beta\rvert}$	$\frac{\lvert\varphi\rvert}{\lvert v_e\rvert}$ (deg/ft per sec)	Average pilot rating	Standard deviation of pilot rating
4.9	4.95	0.97	0.67	0.11	6.3	1.41
4.6	2.25	2.05	.57	.1	6.1	1.44
4.4	1.70	2.58	.57	.1	4.7	1.79
4.5	1.17	3.82	.57	.1	4.1	1.63
2.2	11.6[1]	.19[1]	.56	.09	8.3	.85
2.2	6.2	.35	.55	.09	6.2	2.00
2.2	3.4	.64	.55	.09	5.5	2.16
2.2	1.9	1.14	.55	.09	3.5	1.48
5.0	8.3	.60	2.33	.39	8.5	.93
5.1	5.91	.86	2.36	.40	7.1	1.14
5.7	2.32	2.45	3.18	.53	6.1	1.75
6.3	1.48	4.23	3.61	.61	5.9	1.73
3.5	14.0	.25	1.81	.30	6.3	1.80
3.6	4.18	.86	1.81	.31	5.3	1.81
3.6	2.7	1.33	1.78	.30	4.0	1.48
3.7	1.69	2.18	1.98	.33	4.2	1.83
2.1	7.22[1]	.29[1]	1.02	.17	8.5	1.07
2.1	105.0	.02	1.16	.20	6.0	1.23
2.1	7.7	.27	1.0	.17	5.5	2.09
2.1	1.71	1.22	1.25	.21	3.7	1.65
4.2	∞	0	3.87	.66	9.0	0
4.1	5.73	.72	3.64	.61	7.5	1.12
4.4	3.15	1.4	4.45	.76	7.4	1.41
4.8	1.71	2.80	5.21	.88	7.4	1.01
3.2	30.5[1]	.10[1]	3.38	.57	8.7	0
3.2	7.20	.45	2.85	.48	6.4	1.60
3.2	3.65	.89	3.06	.51	6.4	1.97
3.4	1.85	1.86	3.26	.54	5.9	2.12
2.0	5.40[1]	.37[1]	1.735	.29	8.7	0
2.0	∞	0	1.725	.29	8.0	1.19
2.1	5.0	.42	2.13	.36	6.2	1.91
2.0	2.10	.95	1.8	.30	5.1	1.87
3.6	17.13	.21	5.09	.86	9.0	0
3.7	4.5	.82	5.83	.98	8.2	.75
3.8	2.30	1.65	5.96	1.0	7.5	1.06
3.0	33.33	.09	4.06	.69	9.0	0
3.0	5.0	.60	4.18	.71	8.2	.64
3.1	2.38	1.30	4.72	.80	7.1	1.16
2.0	33.33[1]	.06[1]	2.58	.44	9.0	0
2.0	12.5	.16	3.22	.54	7.9	1.11
2.0	2.57	.80	2.78	.47	6.3	1.29

[1]Oscillations unstable; values for T_2 and $1/C_2$ are given.

TABLE II.– PILOTS' OPINIONS OF CONFIGURATIONS EXHIBITING MEASURABLE APERIODIC DIVERGENCE

Flight condition	T_{2_a} (sec)	Average pilot rating	Standard deviation of pilot rating
Cruising	3.9	8.0	1.33
Do.	6.0	7.0	1.37
Landing approach	1.5	8.6	.49
Do.	1.7	8.2	1.07
Do.	2.0	7.1	1.65
Do.	3.0	6.4	1.08

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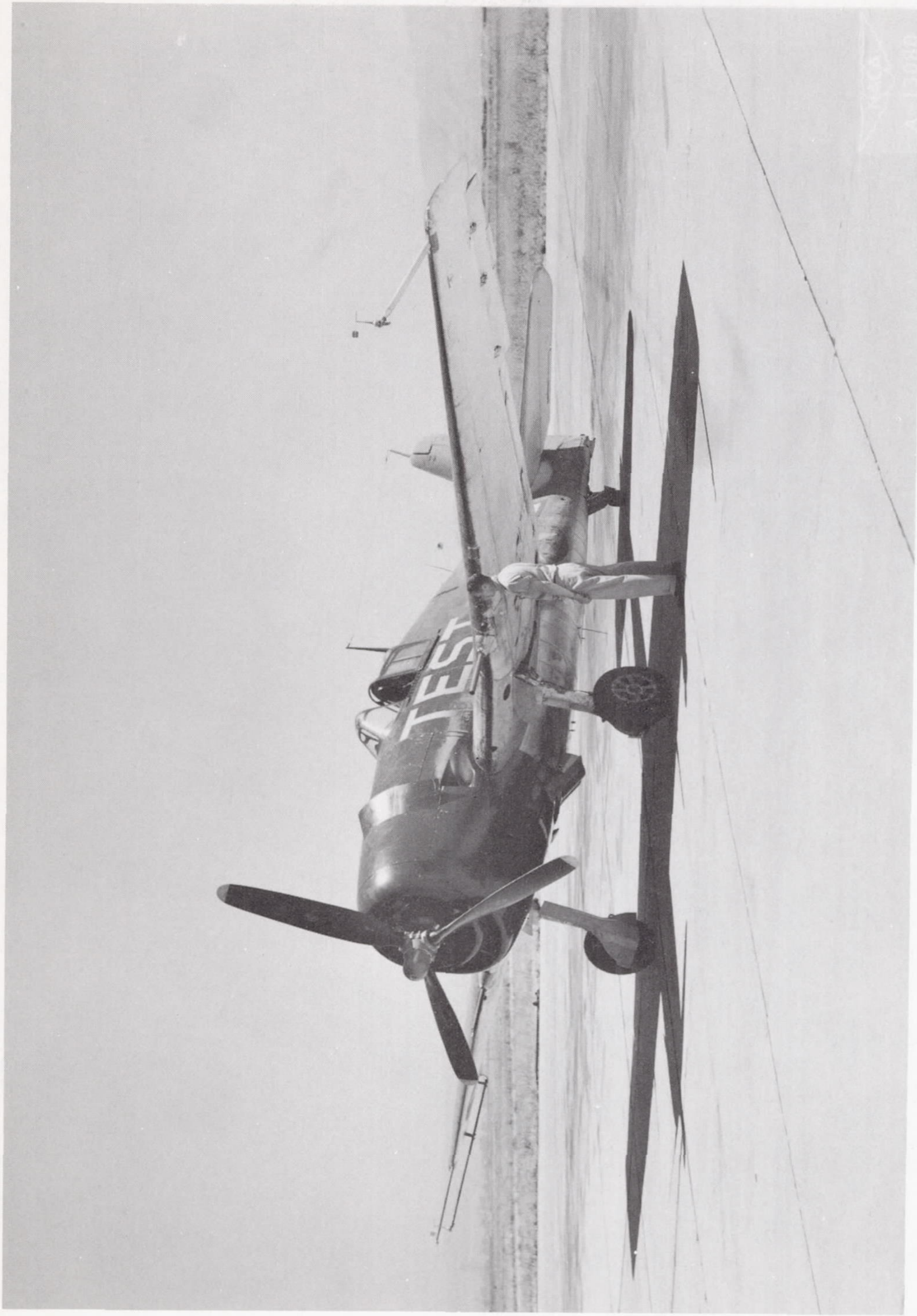
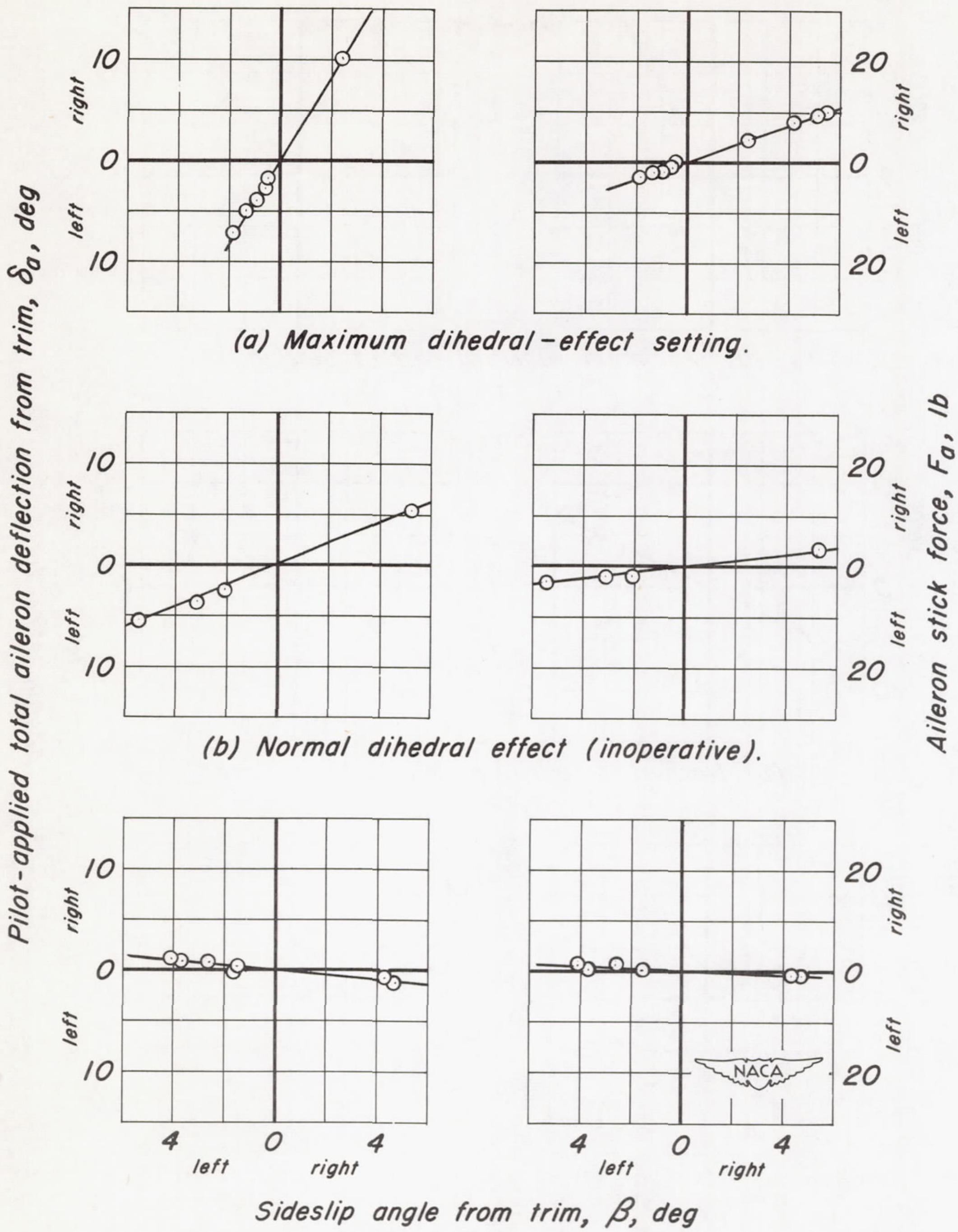


Figure 1.- Three-quarter front view of test airplane instrumented for flight.

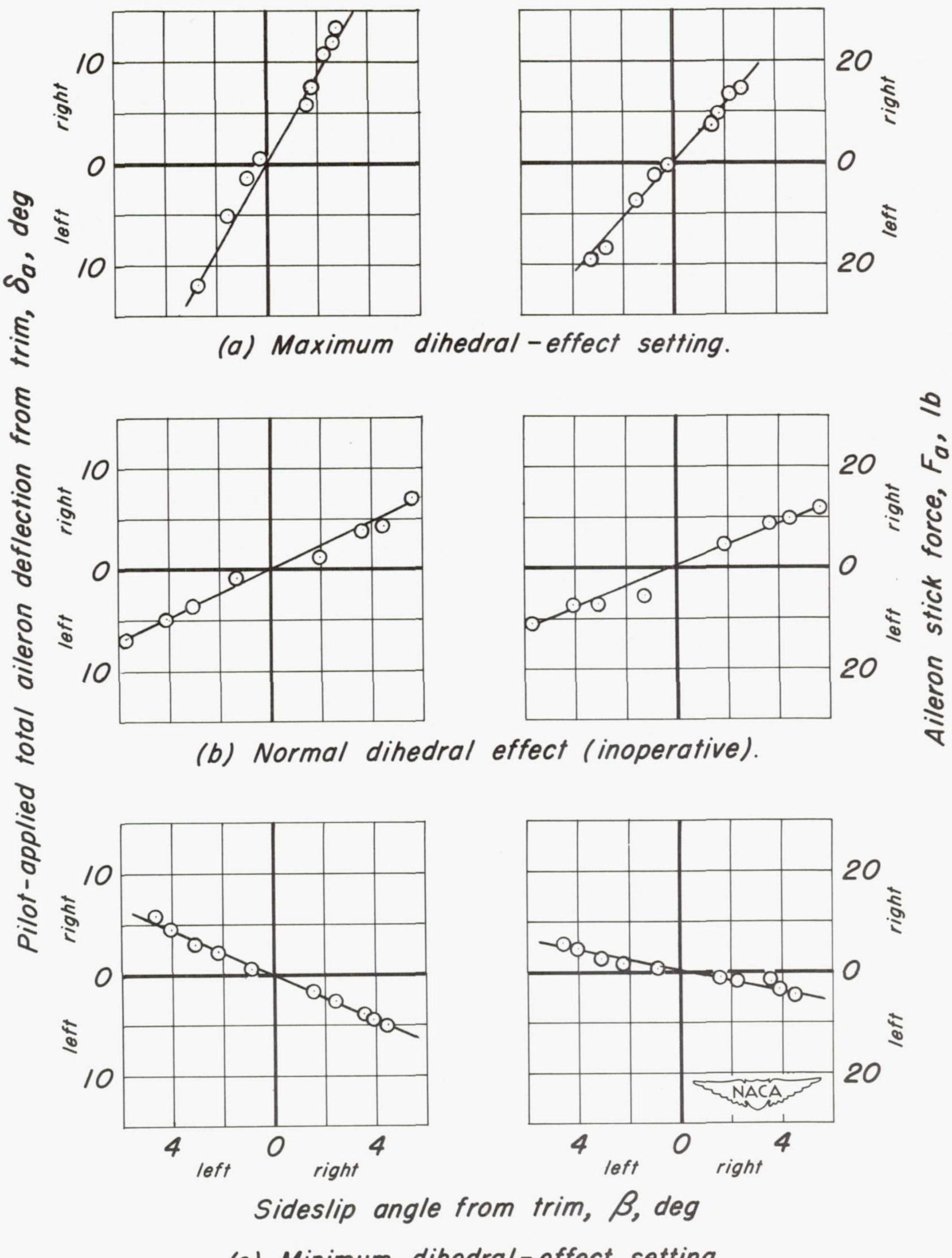


(a) Maximum dihedral-effect setting.

(b) Normal dihedral effect (inoperative).

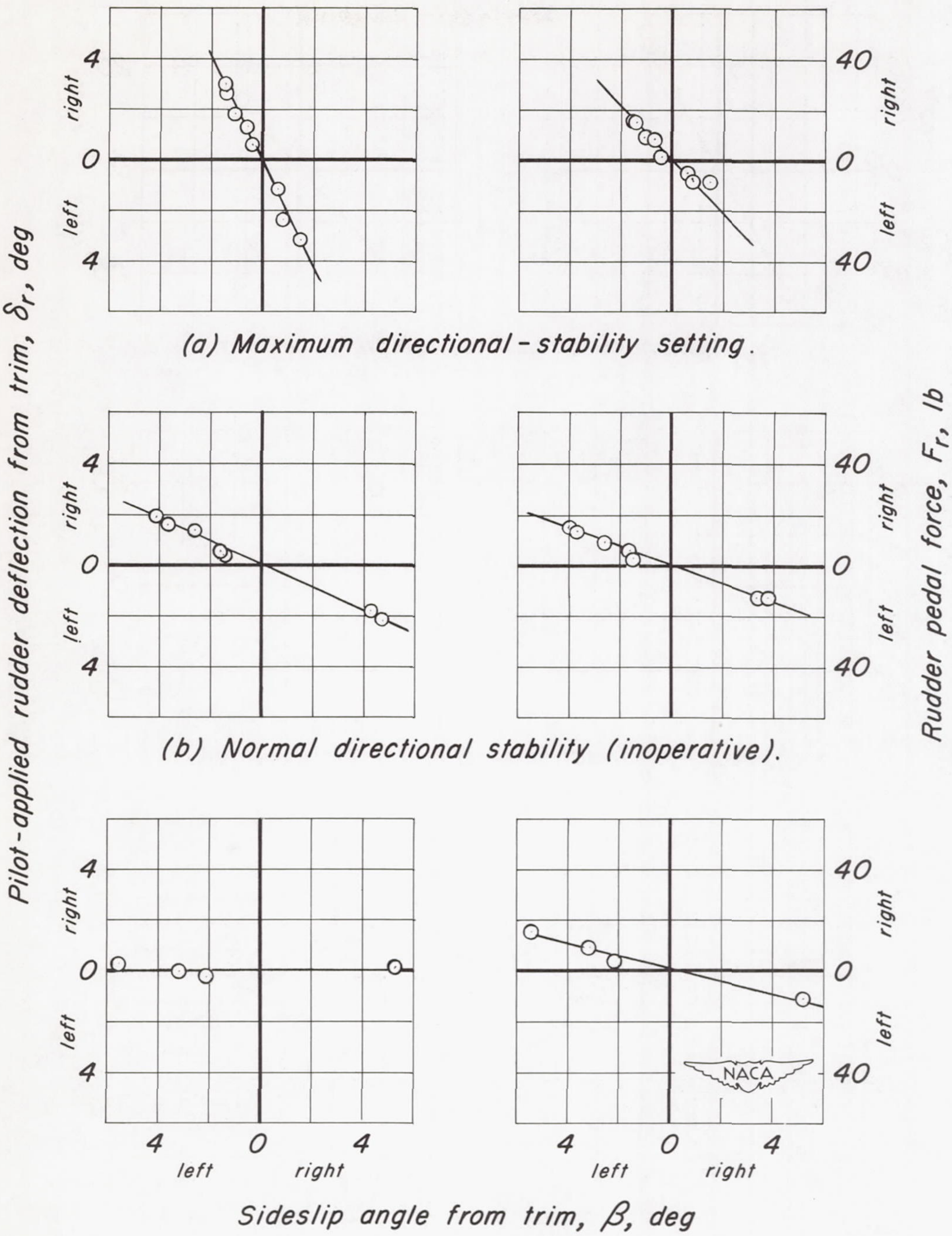
(c) Minimum dihedral-effect setting.

Figure 2.- Lateral stability and control characteristics during steady, straight sideslips. Landing-approach condition.



(c) Minimum dihedral-effect setting.

Figure 3.– Lateral stability and control characteristics during steady, straight sideslips. Cruising condition.



(c) Minimum directional-stability setting.

Figure 4.- Directional stability and control characteristics during steady, straight sideslips. Landing-approach condition.

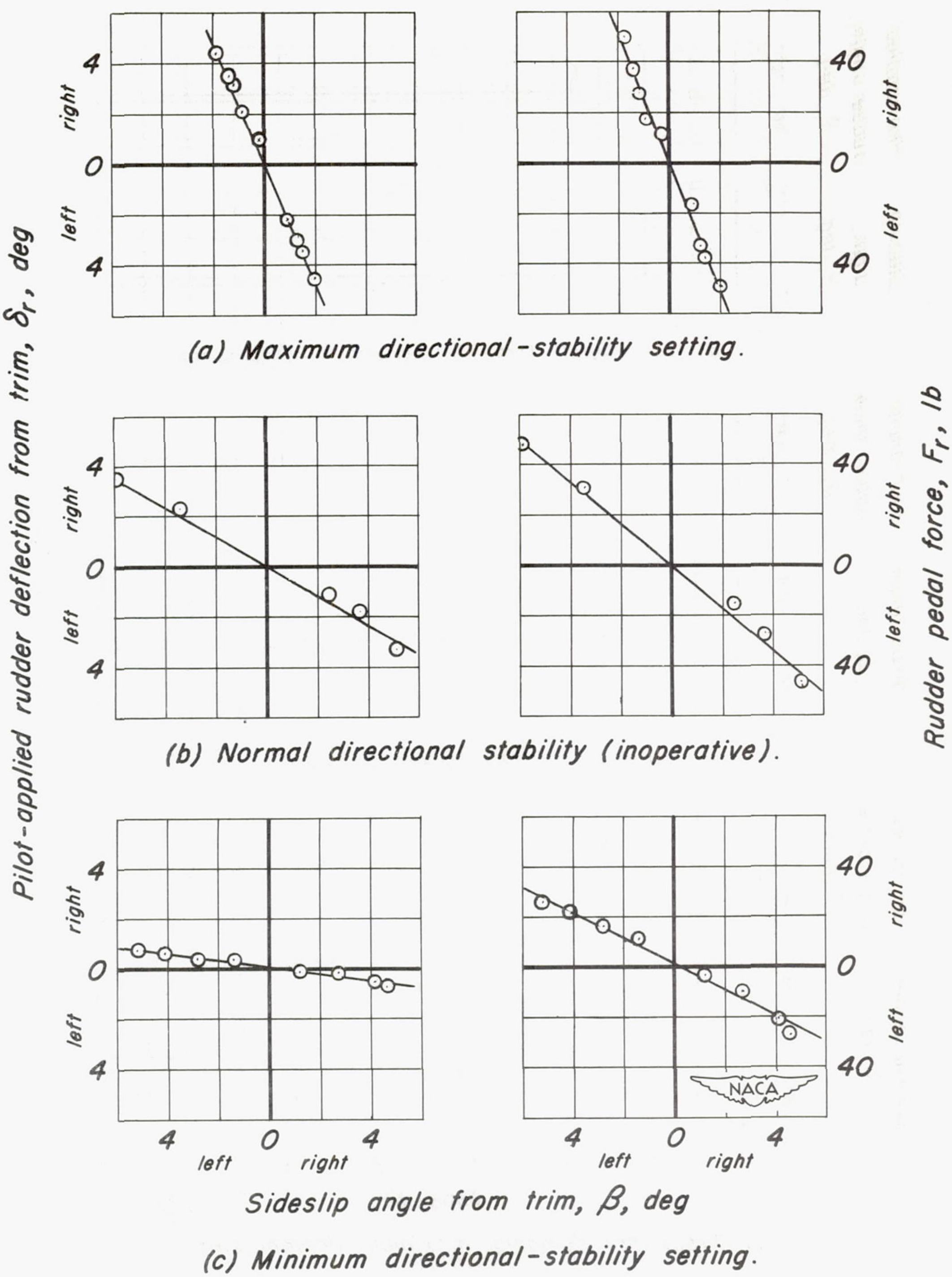
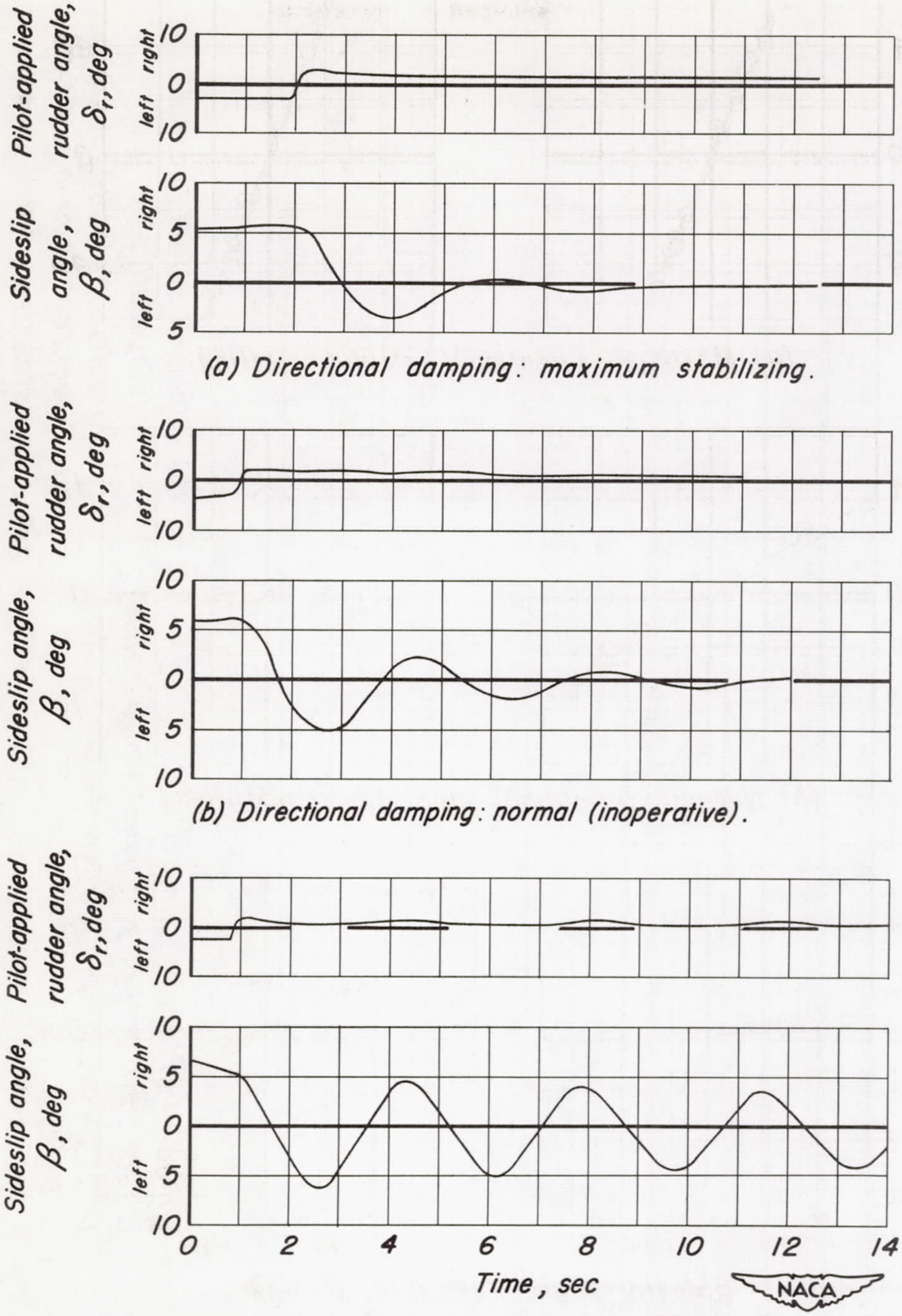


Figure 5.– Directional stability and control characteristics during steady, straight sideslips. Cruising condition.

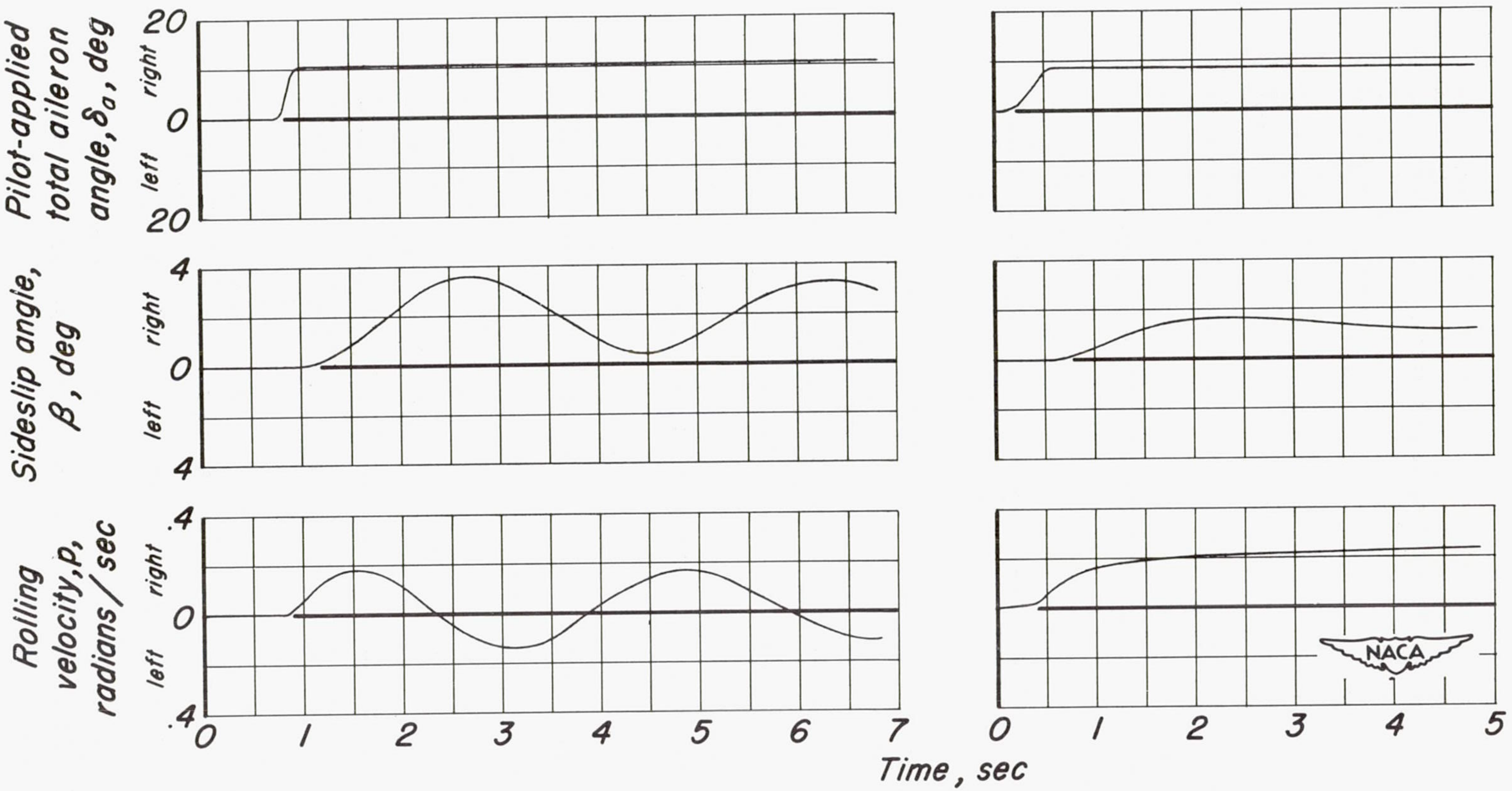


(a) Directional damping: maximum stabilizing.

(b) Directional damping: normal (inoperative).

(c) Directional damping: maximum destabilizing.

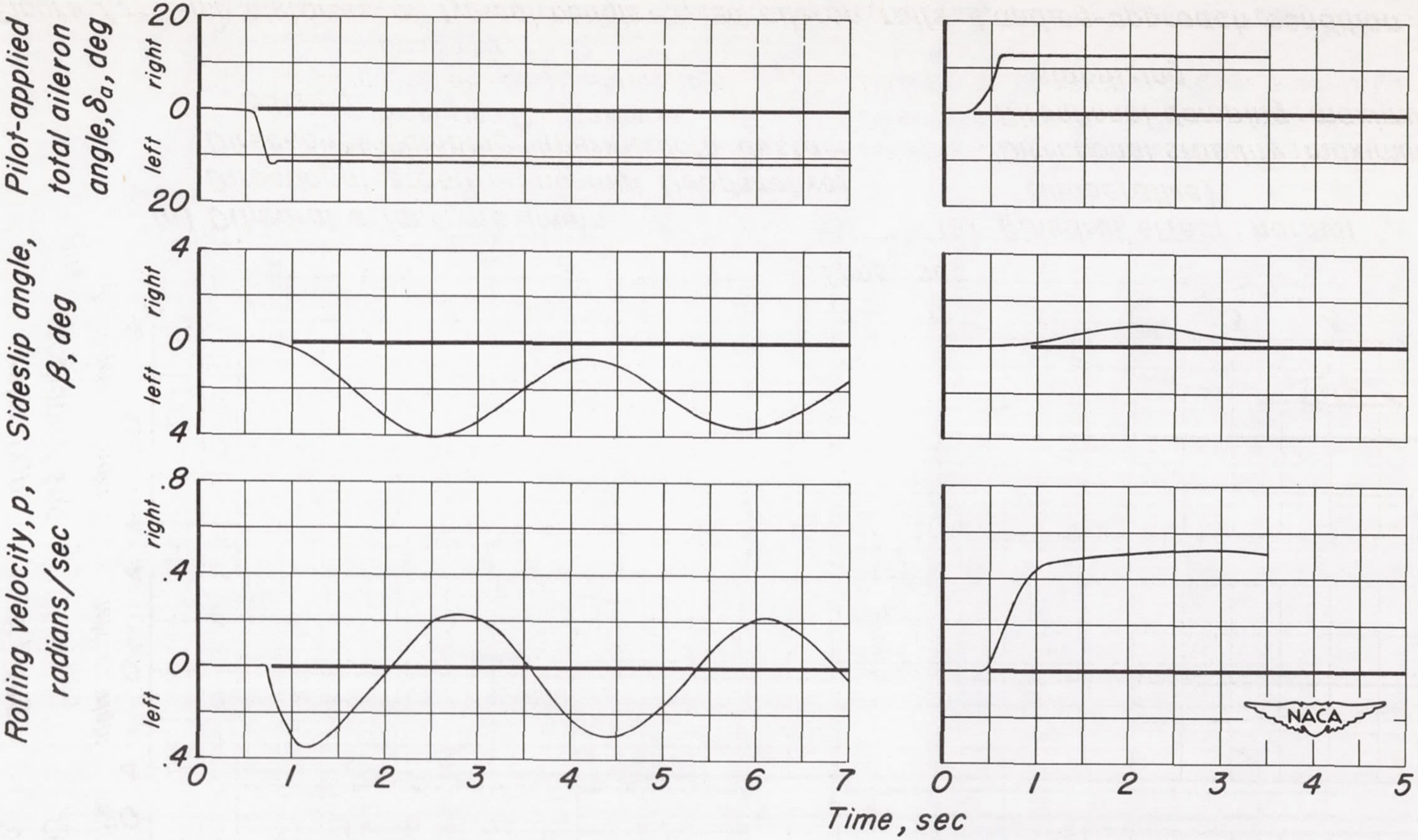
Figure 6.– Time histories of typical controls-fixed lateral oscillations with dihedral effect and directional stability normal. Cruising condition.



(a) Dihedral effect: maximum.
Directional stability: normal (inoperative).
Directional damping: intermediate destabilizing.

(b) Dihedral effect: normal (inoperative).
Directional stability: maximum.
Directional damping: maximum stabilizing.

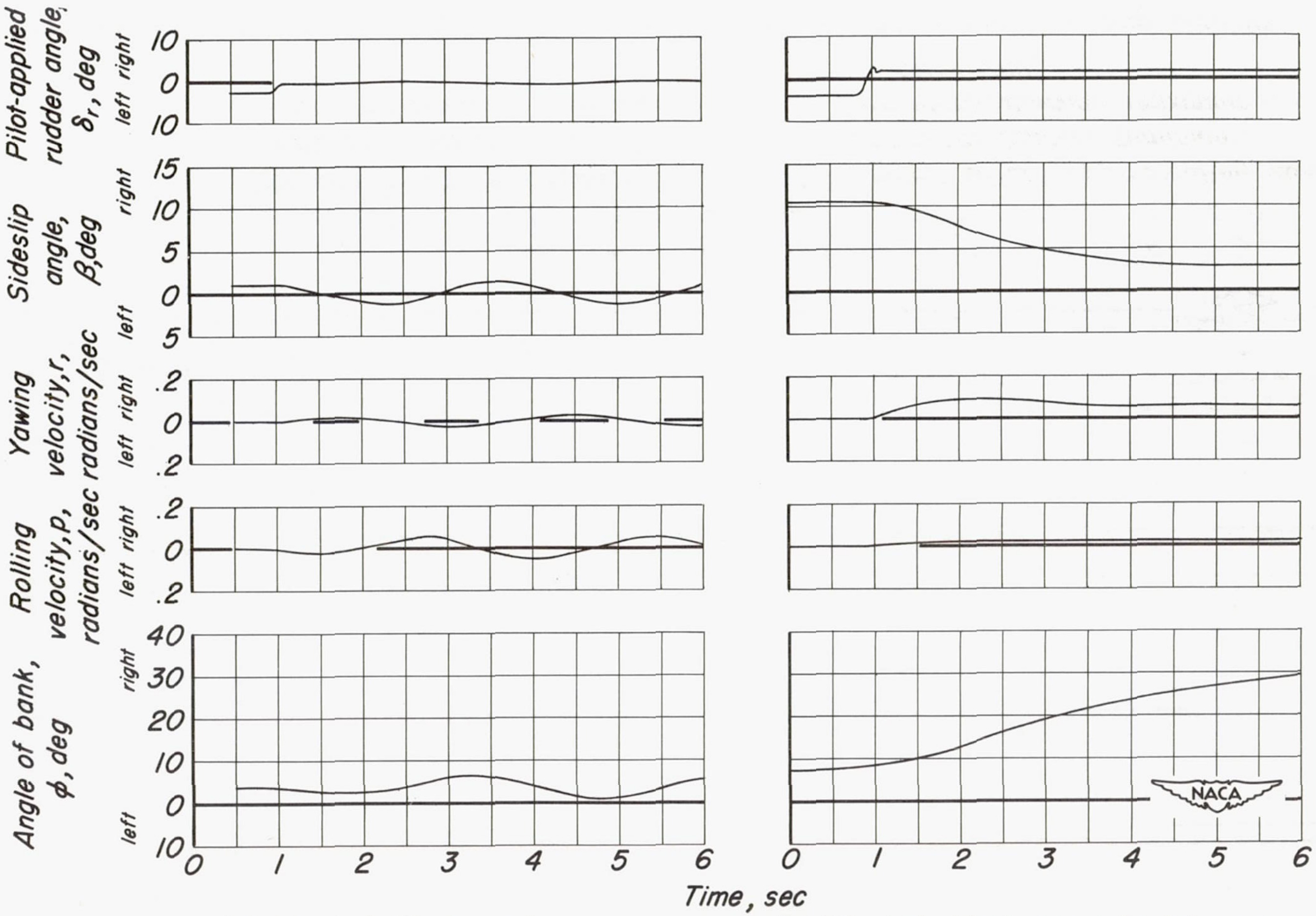
Figure 7.— Time histories of typical pedals-fixed aileron rolls. Landing-approach condition.



(a) Dihedral effect: maximum.
Directional stability: minimum.
Directional damping: intermediate destabilizing.

(b) Dihedral effect: approximately zero.
Directional stability: maximum.
Directional damping: normal (inoperative).

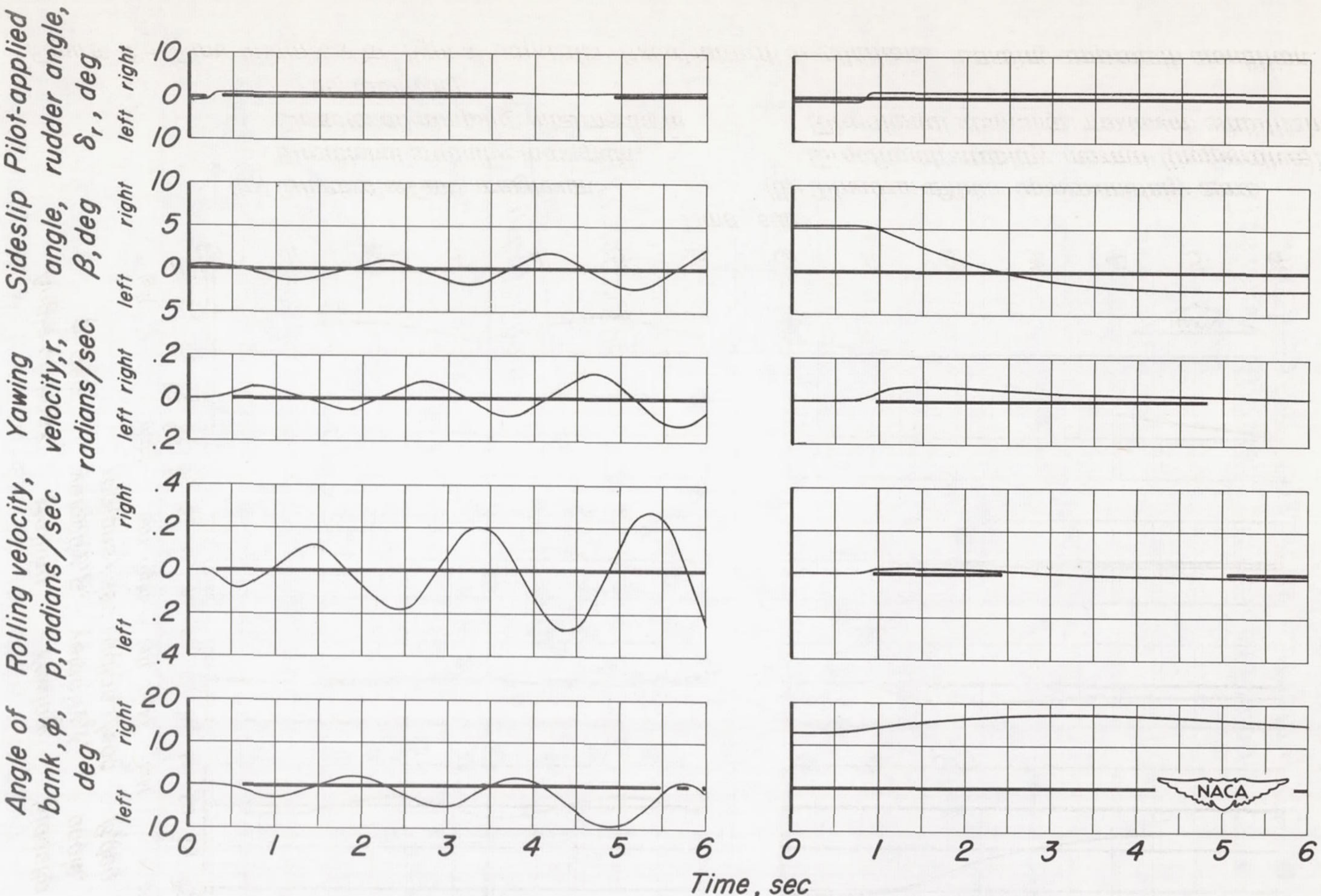
Figure 8.– Time histories of typical pedals – fixed aileron rolls. Cruising condition.



(a) Dihedral effect: maximum.
Directional stability: maximum.
Directional damping: intermediate destabilizing.

(b) Dihedral effect: approximately zero.
Directional stability: normal (inoperative).
Directional damping: maximum stabilizing.

Figure 9.– Time histories of typical controls-fixed lateral oscillations. Landing-approach condition.



(a) Dihedral effect: maximum.
Directional stability: maximum.
Directional damping: maximum destabilizing.

(b) Dihedral effect: approximately zero.
Directional stability: minimum.
Directional damping: maximum stabilizing.

Figure 10.– Time histories of typical controls – fixed lateral oscillations. Cruising condition.

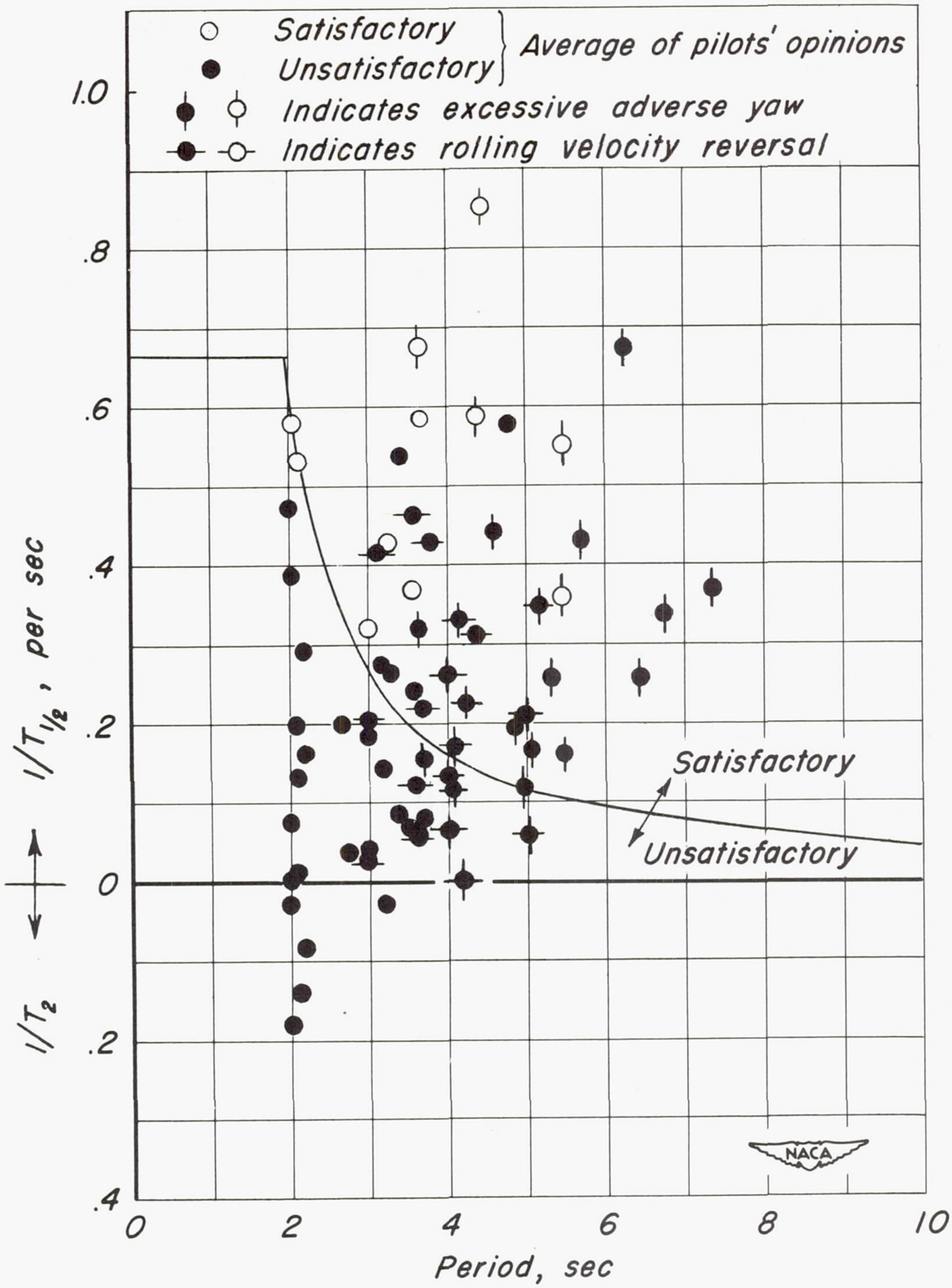


Figure 11.- A comparison of pilots opinion with lateral oscillatory requirements of references 1 and 2.

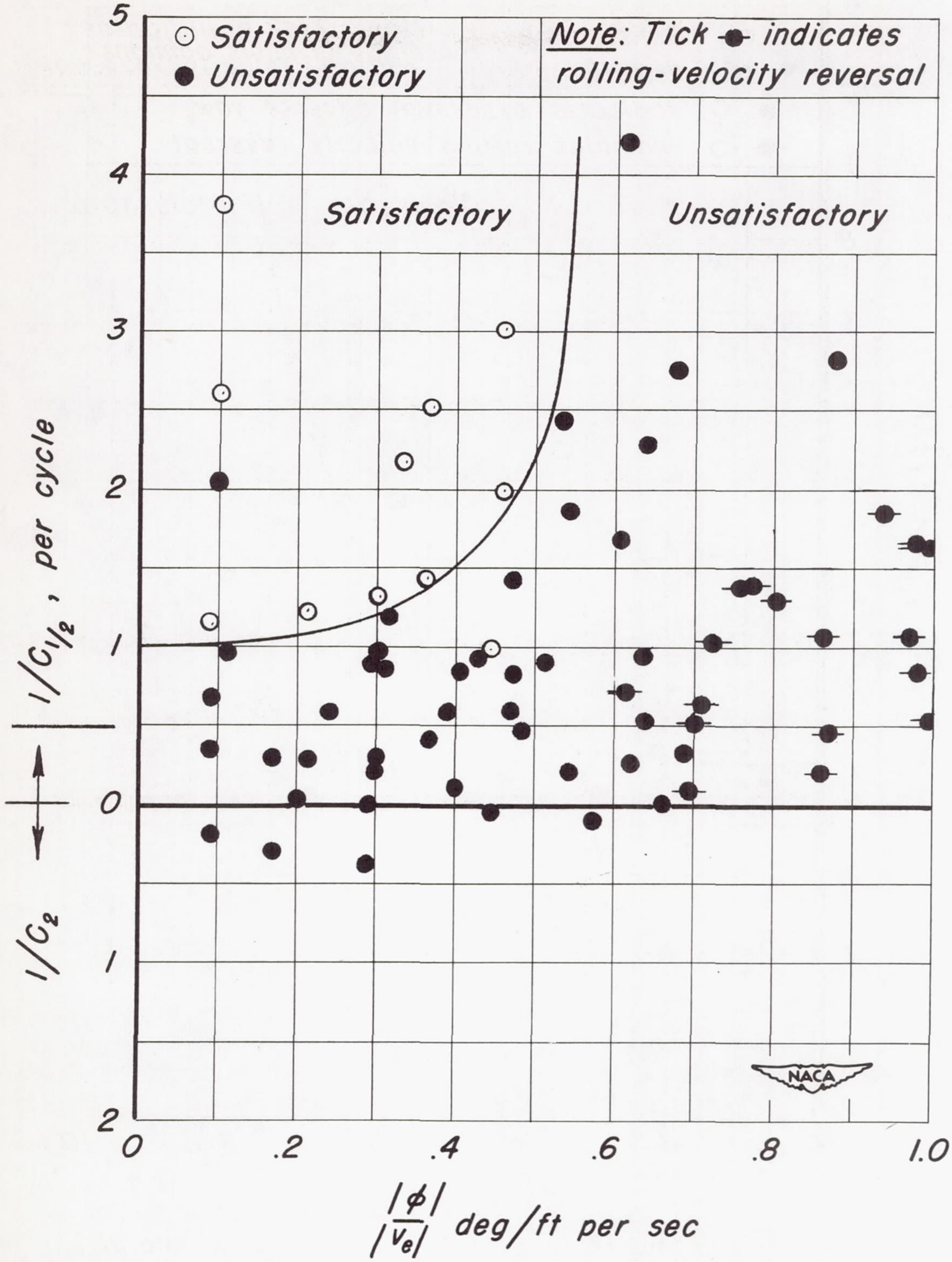


Figure 12.– Boundary between satisfactory and unsatisfactory lateral oscillatory characteristics.

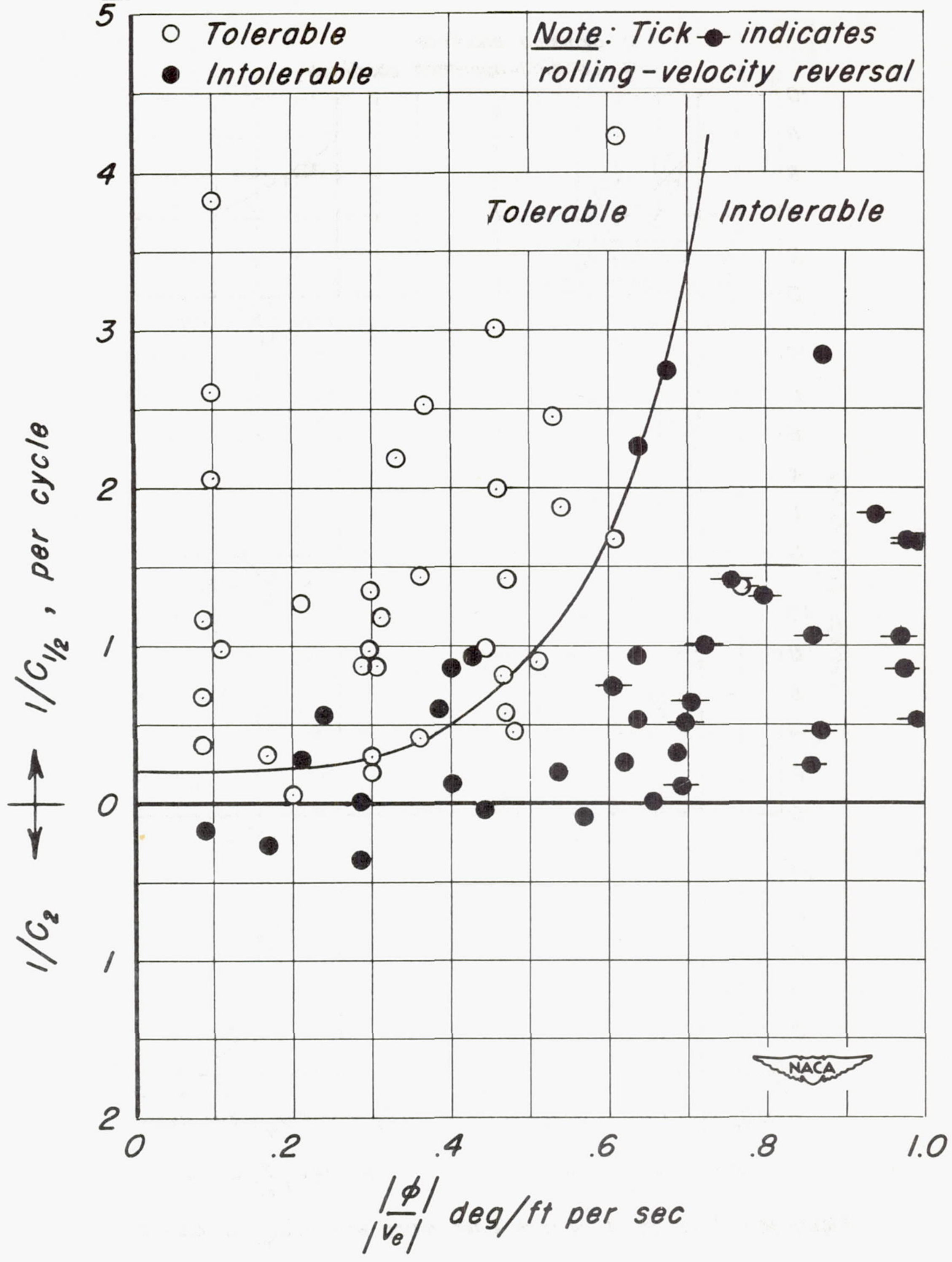


Figure 13.- Boundary between tolerable and intolerable lateral oscillatory characteristics.

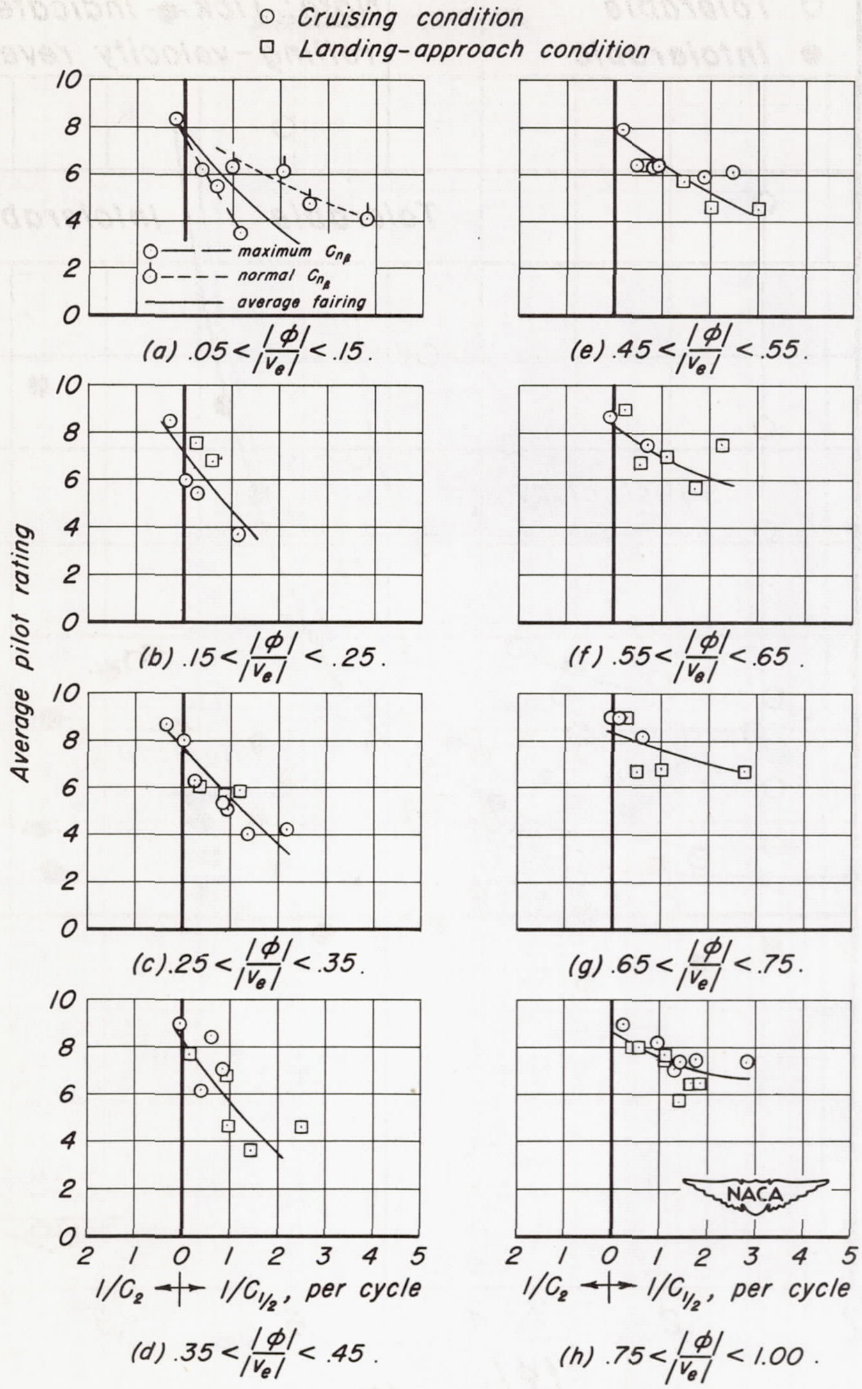


Figure 14.- Variation of average pilot rating with $1/C_{1/2}$ for approximately constant values of $\frac{|\phi|}{|v_e|}$

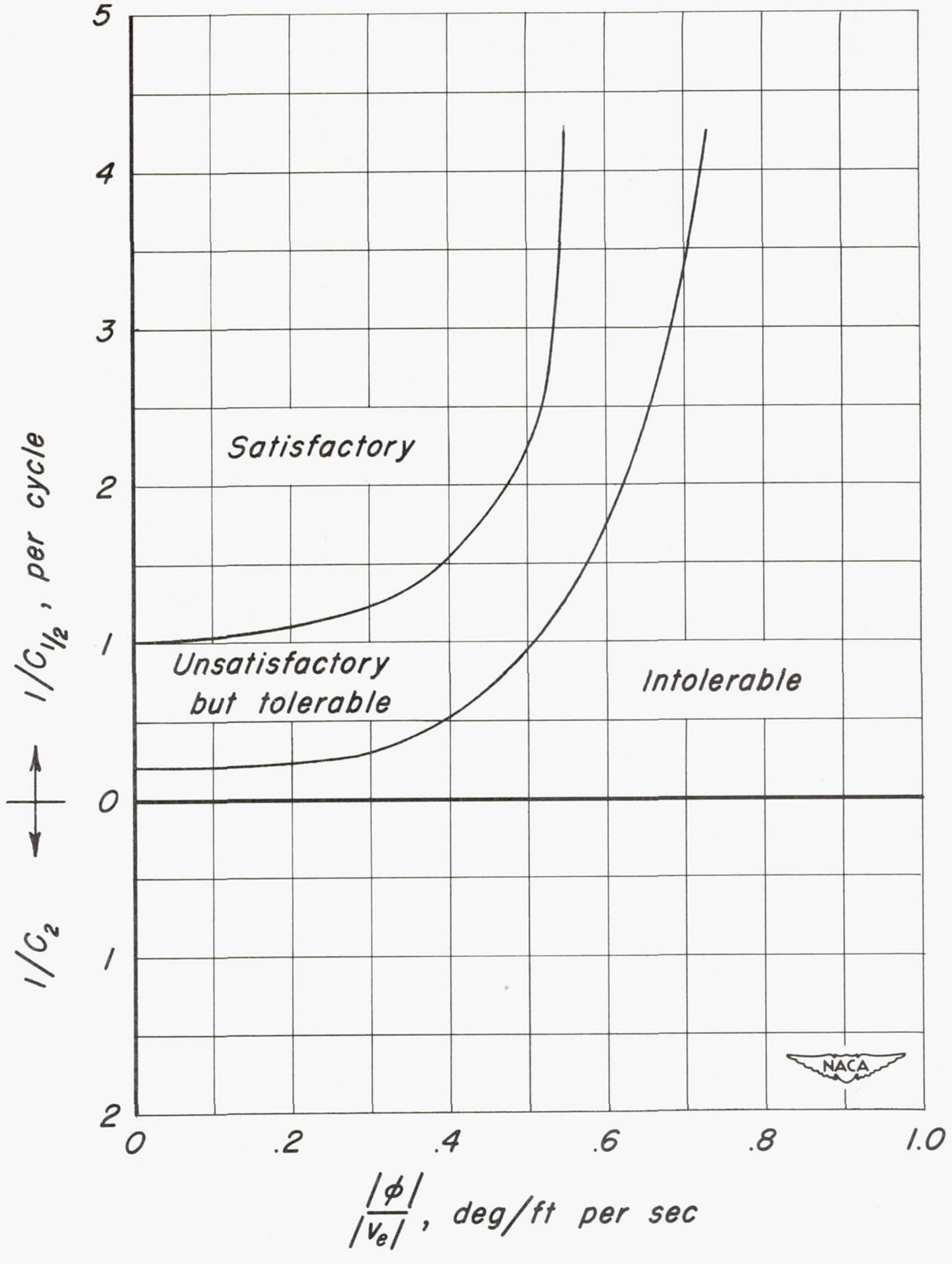


Figure 15.- Proposed tentative boundary between satisfactory and unsatisfactory and between tolerable and intolerable lateral oscillatory characteristics.

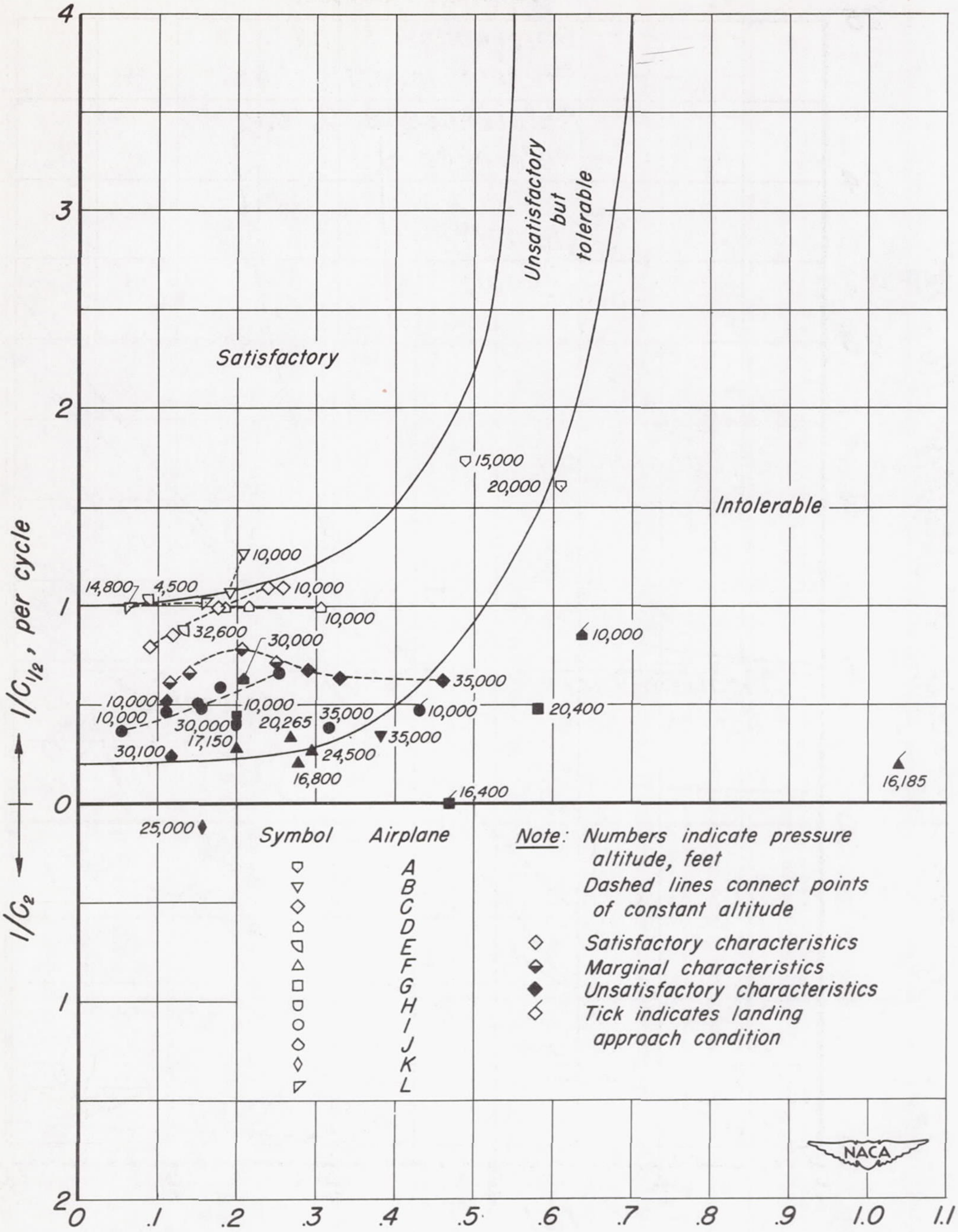


Figure 16.– Comparison of lateral oscillatory characteristics of several present day aircraft with proposed tentative boundaries including pilots opinions of the motions.

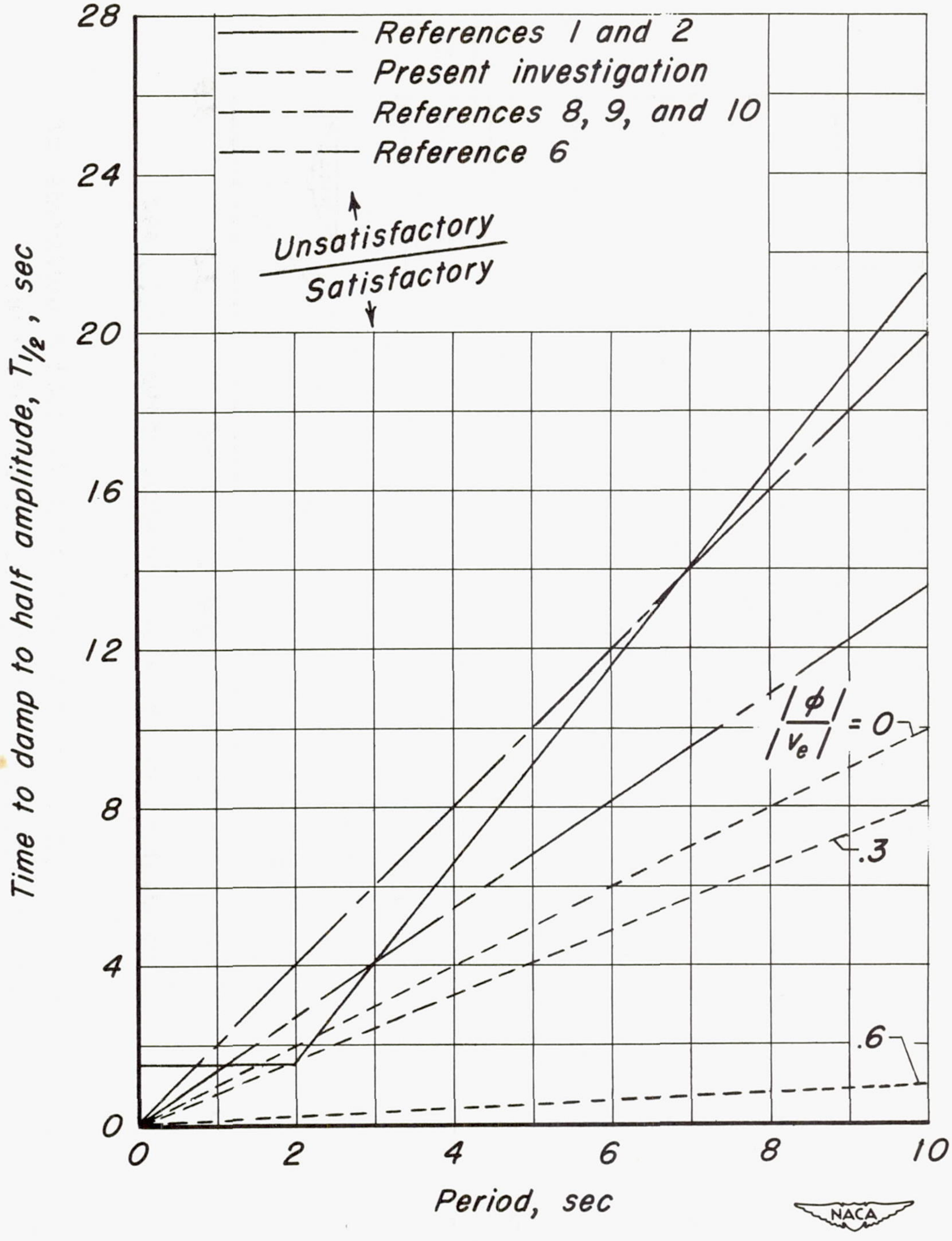


Figure 17.– Boundary between satisfactory and unsatisfactory lateral oscillatory characteristics from references indicated.

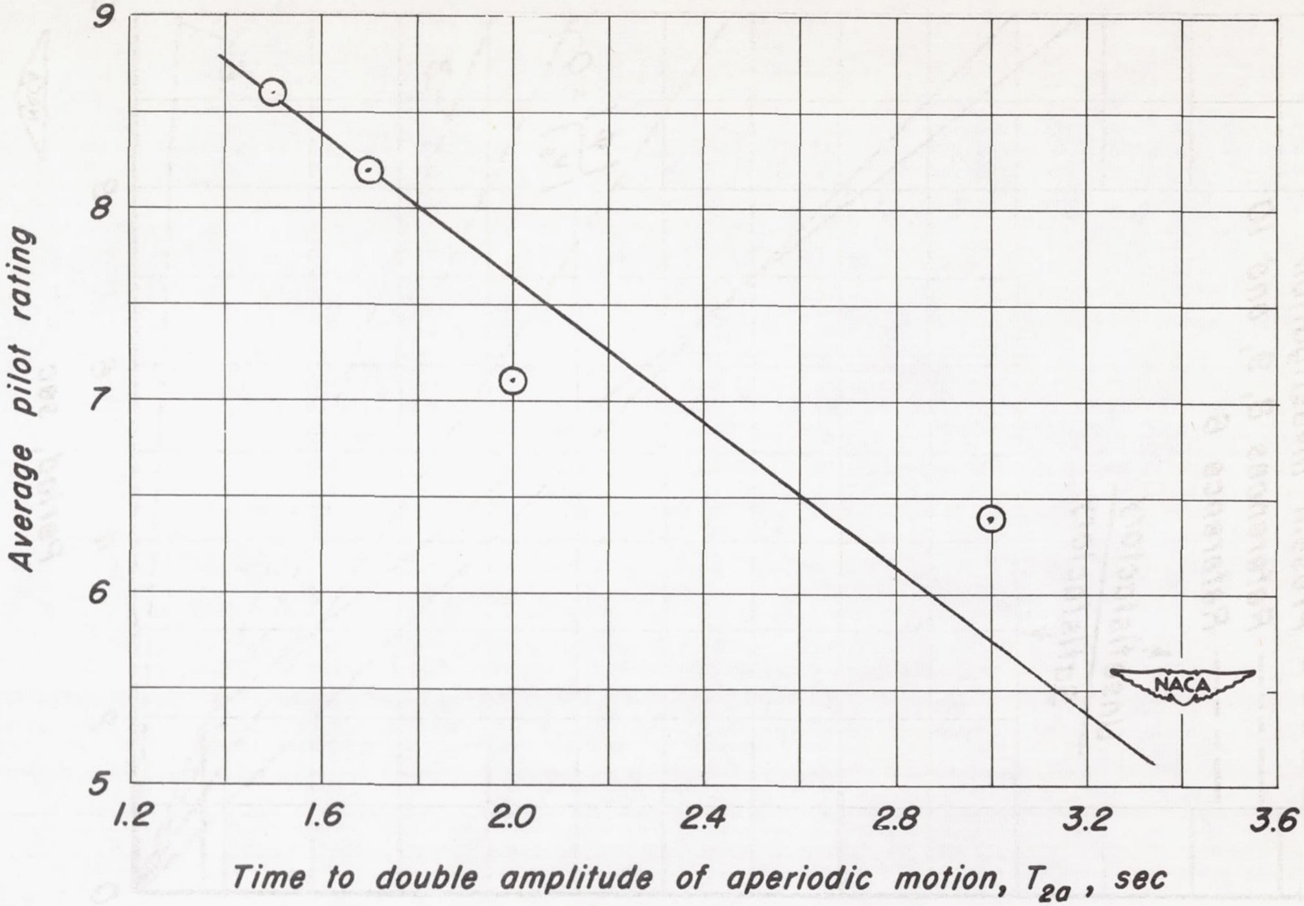


Figure 18.– Variation of pilot ratings with time to double amplitude of aperiodic motion. Landing - approach condition.

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